

# $W/Z + \text{jet}$ production

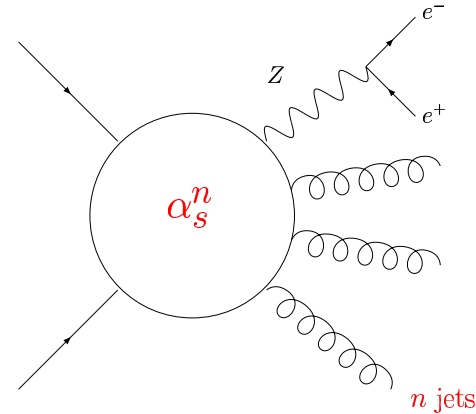
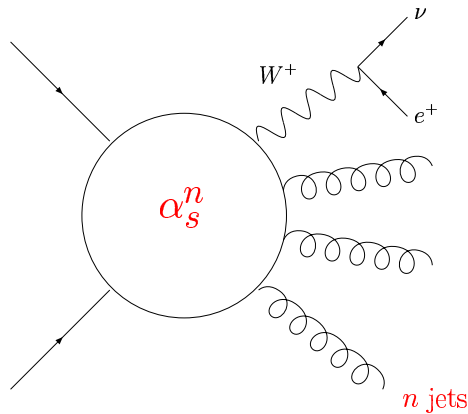
15th Topical Conference on  
Hadron Collider Physics

John Campbell  
*Argonne National Laboratory*

# Outline

- Motivation for studying  $W/Z + \text{jets}$
- Review of Run I studies
  - ★ Theoretical tools
  - ★ Experimental results
- Run II status
  - ★ Advances in theory
  - ★ Impact on current studies
- Areas for improvement
- Summary and outlook

# Motivation



## ■ A good test of QCD

- ★  $W/Z + n$  jets cross-section proportional to  $\alpha_s^n$  in lowest order
- ★ Many jets means that we can test features such as clustering schemes
- ★ Presence of a heavy boson suggests that perturbation theory should be reliable
- ★  $Z +$  jets is relatively free from backgrounds and can be used to test the accuracy of theoretical predictions for  $W +$  jets

# Generic background

- $W + \text{jets}$  final state is

$$\text{lepton} + E_T^{miss} + \text{jets}$$

- A background to almost every interesting process one could think of, especially when combined with misidentification and limited detector coverage
- $Z + \text{jets}$  final state is **dileptons + jets** which yields information about the invisible decay of the  $Z$ , which would be:

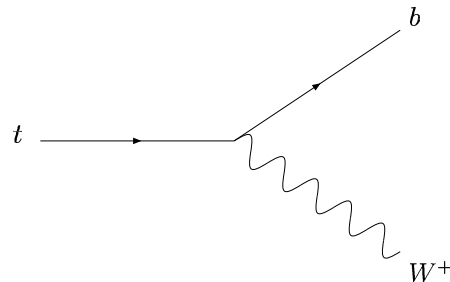
$$E_T^{miss} + \text{jets}$$

- A way to calibrate this important background for many new particles which appear only as missing  $E_T$

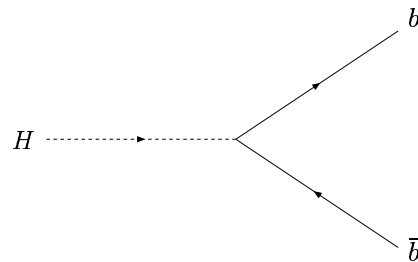
# Heavy quark background

- If the jets are tagged as heavy quarks, it's an even more important background

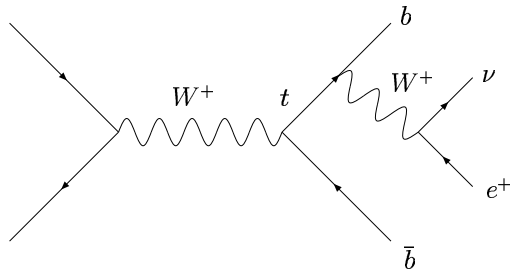
- ★ Top decays  $t \rightarrow W + b$



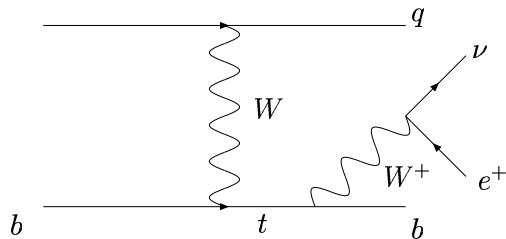
- ★ Much new physics couples preferentially to massive quarks, for instance a light Higgs with  $m_H < 140$  GeV decaying to  $b\bar{b}$



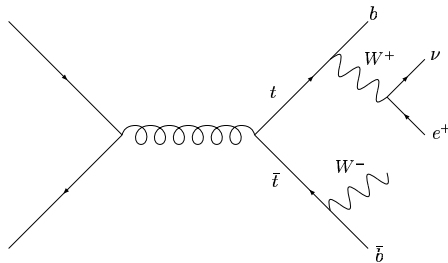
# Top processes



→ 2 jets, both  $b$ 's



→ 2 jets, only one is a  $b$

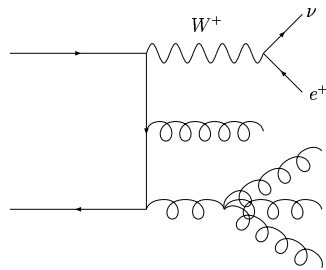


→  $\geq 2$  jets, two are  $b$ 's

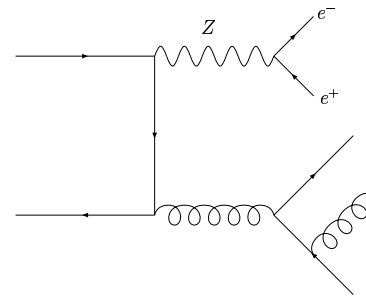
# Review of Run I

- The state of the art QCD prediction at the beginning of Run I was given by the leading order Monte Carlo program VECBOS

Berends et al., 1991



$W + 4$  jets



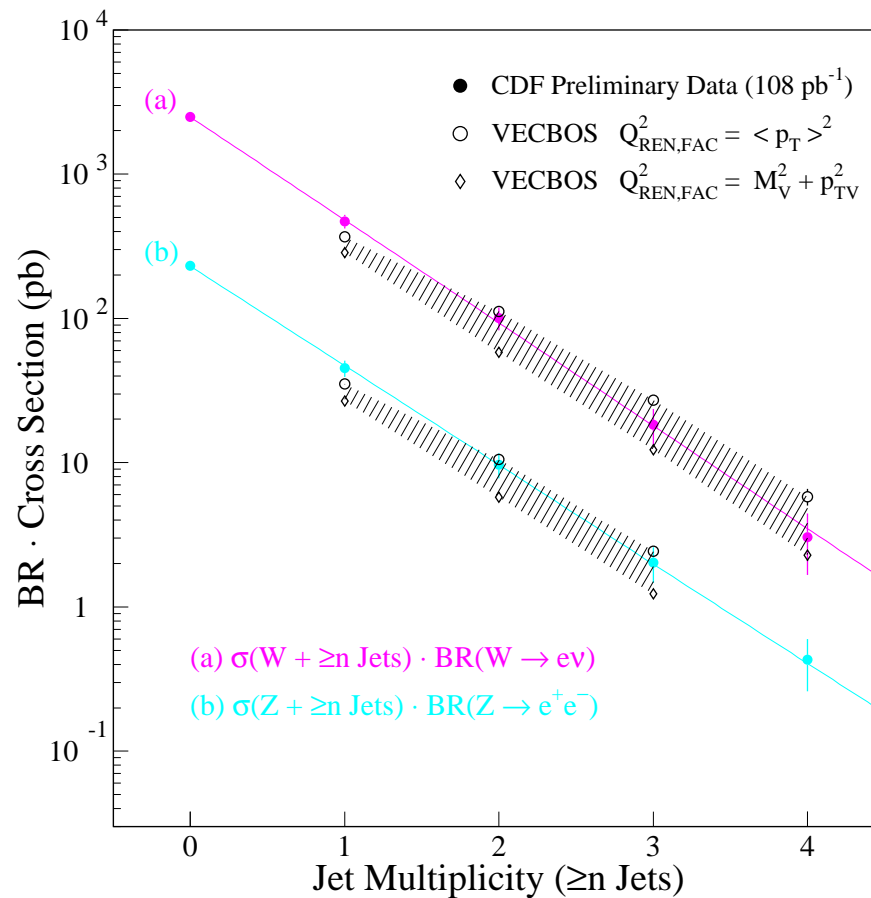
$Z + 3$  jets

- "Enhanced leading order" uses HERWIG to add a parton shower and hadronization. High jet multiplicity states only included via the shower.
- Predictions for the production of heavy quarks in association with a vector boson,  $Wb\bar{b}$  and  $Zb\bar{b}$  are available at LO also

# $W/Z + \text{jet}$ cross-sections in Run I

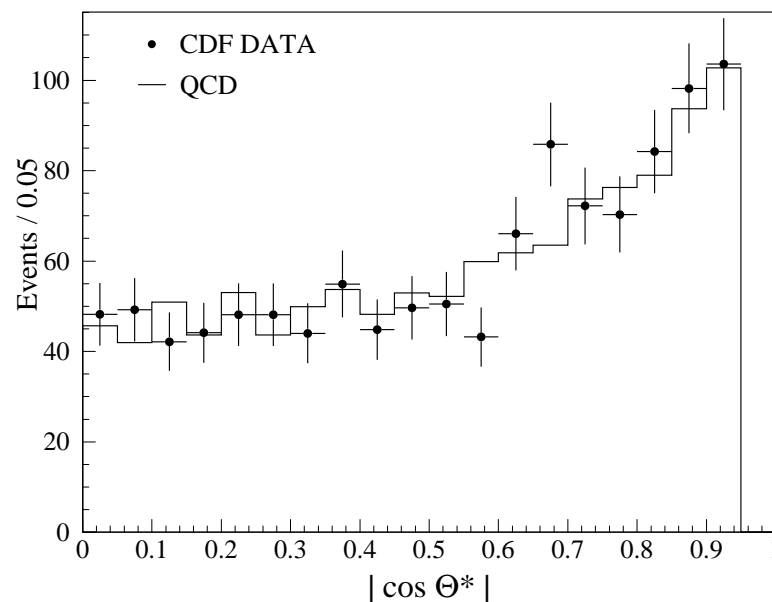
■ Rates for  $W/Z + n$  jets in Run I, compared to leading order theory

CDF collaboration, Moriond 1997



# $Z + \text{jets in Run I}$

- Measurements of some kinematic properties were also made, for instance in the  $Z + \geq 1$  jet sample:

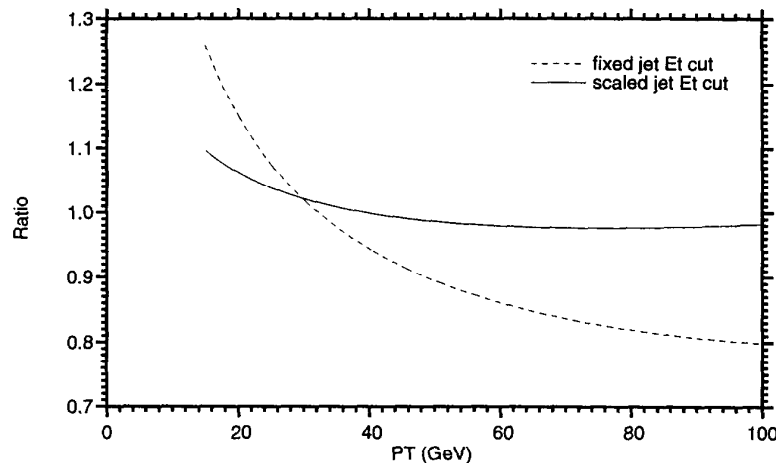


- Angle  $\Theta^*$  between the  $Z$  and the average beam direction, in the  $Z +$  leading jet c.o.m. frame  
F. Abe et al, CDF collaboration, FERMILAB-PUB-96/056-E (1996)
- Good agreement, with the prediction normalized to the data

# Testing QCD

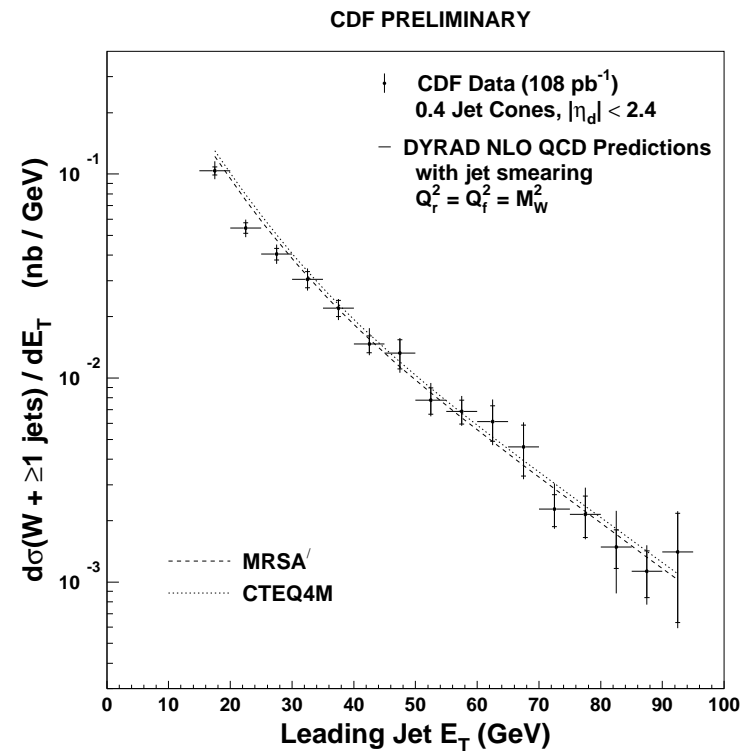
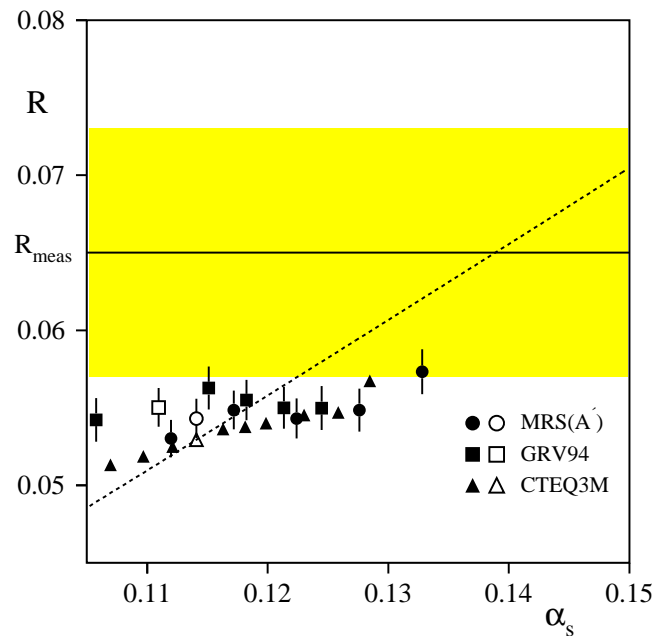
- More precise tests became possible with the advent of a differential NLO calculation of the  $W/Z + 1$  jet rates in DYRAD  
W. Giele, E. W. N. Glover and D. Kosower (1993)
- The normalization of the cross-section can now be taken seriously
- In addition, higher order effects may change the shapes of some distributions

FIG. 9. The ratio of next-to-leading order to leading order jet transverse momentum distributions for a fixed  $E_{T\min}^{\text{jet}} = 15$  GeV cut and for a scaled  $E_{T\min}^{\text{jet}} = \max(15 \text{ GeV}, 0.1 \times \sqrt{\hat{s}})$  cut as a function of the jet transverse momentum.



# $W + 1 \text{ jet} / W + 0 \text{ jet ratio}$

- D0 measurement of the ratio of  $W + 1$  to  $W + 0$  jet cross-sections,  $\mathcal{R}$  from early Run I data



- Newer measurement by CDF, as a function of the leading jet  $E_T$

# Run II predictions

- Technical improvements have led to leading order predictions for  $W, Z + n$  jets processes to higher jet multiplicities.

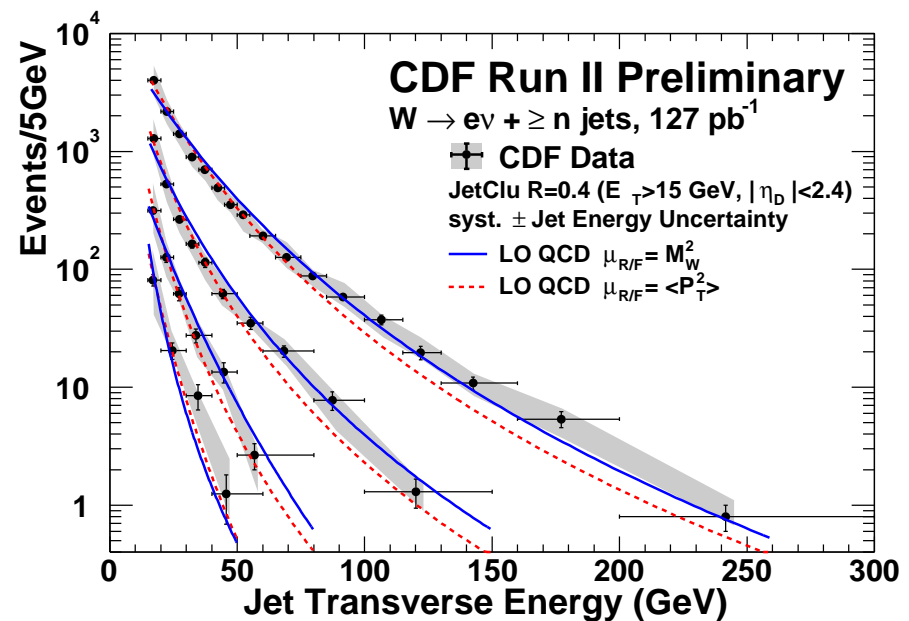
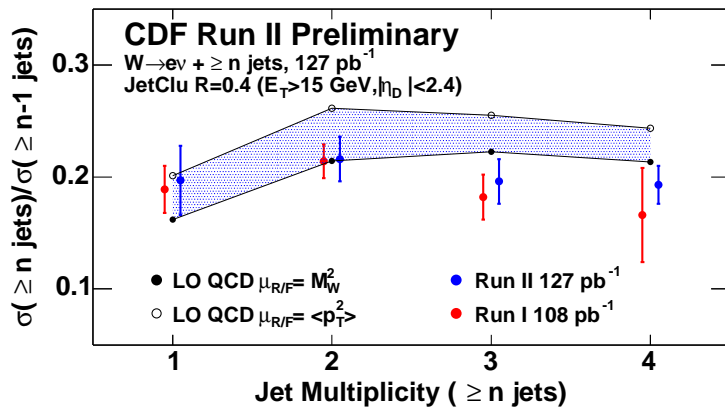
ALPGEN, hep-ph/0206293

Madevent, hep-ph/0208156

- For example, ALPGEN includes matrix elements for the production of a vector boson and up to 6 jets, including the case where two of them are heavy quarks.
- In addition, the procedure for combining matrix element programs and parton showers has also improved:
  - ★ A rigorous prescription (CKKW) that retains the benefits of both approaches has existed for some time, for  $e^+e^-$  colliders.  
S. Catani et al., hep-ph/0109231
  - ★ Recent progress has been made in adapting this for use at the Tevatron, in both HERWIG and PYTHIA.  
S. Mrenna and P. Richardson, hep-ph/0312274
  - ★ This is an area of ongoing study.

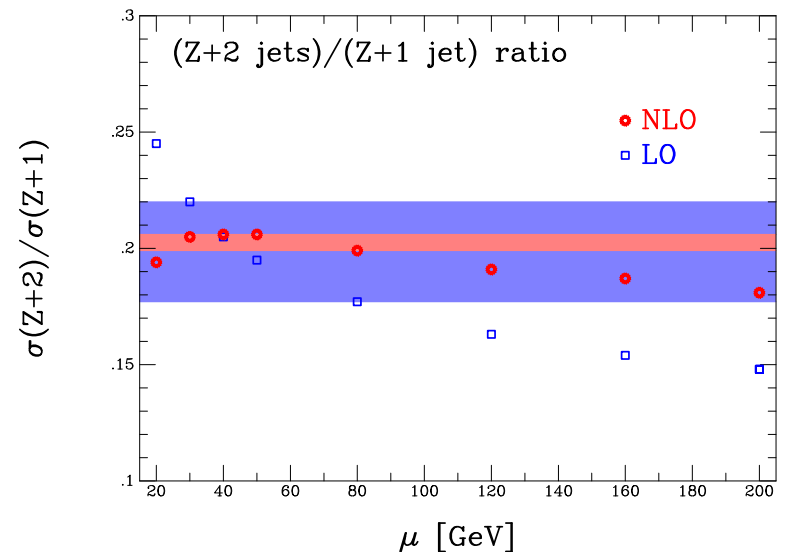
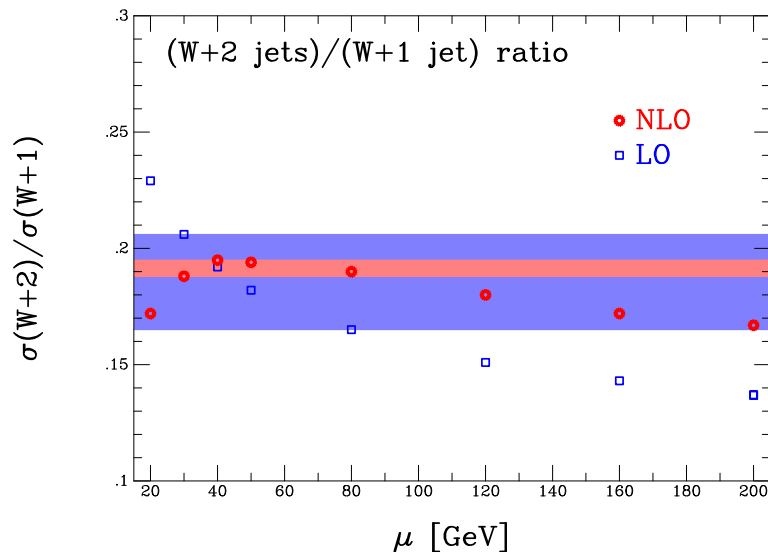
# *W+jet cross-sections from CDF*

## ■ Preliminary Run II CDF comparisons



# NLO advances

- NLO corrections to  $W/Z + 2$  jet production are now available in the Monte Carlo MCFM, together with corresponding results for  $W/Z + Q\bar{Q}$  in the approximation  $m_Q = 0$   
JC and K. Ellis, hep-ph/0202176
- The usual features of NLO hold and, for instance, the prediction for the 2/1 jet ratio is much more stable than at leading order:



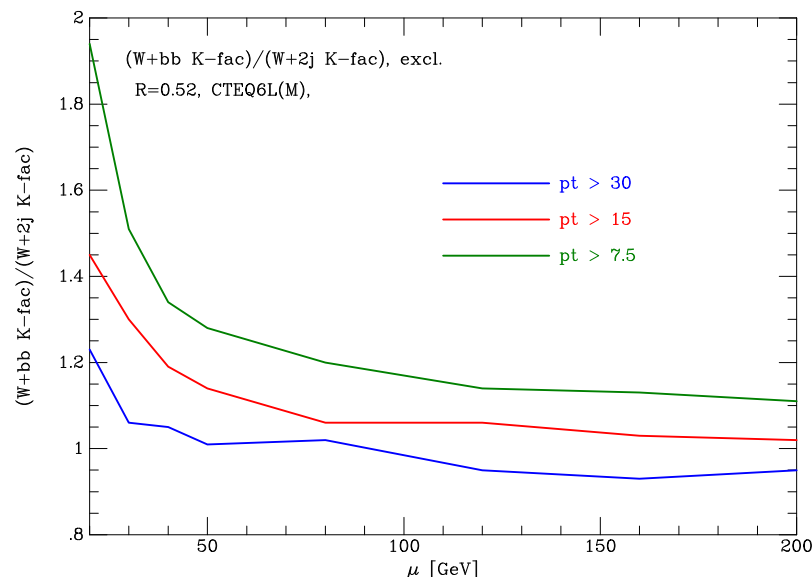
# Heavy flavour content studies

- Some analyses rely on the heavy flavour fraction to estimate backgrounds:

$$\sigma(Wb\bar{b}) = \left[ \frac{\sigma(Wb\bar{b})}{\sigma(W + 2 \text{ jet})} \right]_{MC} \times [\sigma(W + 2 \text{ jet})]_{\text{data}}$$

- The effect of NLO corrections on this method has been extensively studied with respect to variations of scale and jet  $p_T$

JC and J. Huston, hep-ph/0405276

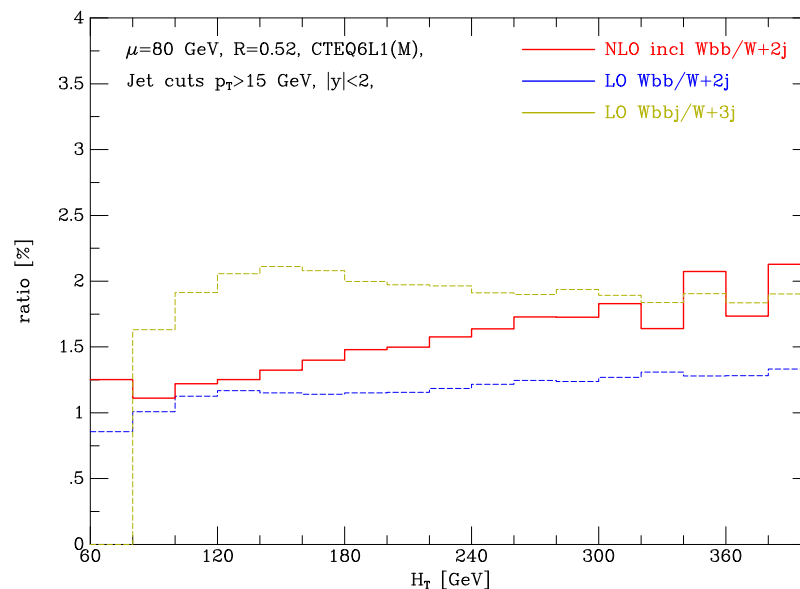


NLO ratio  $\sim 1.2\%$

about the same as  
assumed in Run I

# Caveats

- However, some distributions are not as similar as one might expect when moving to NLO



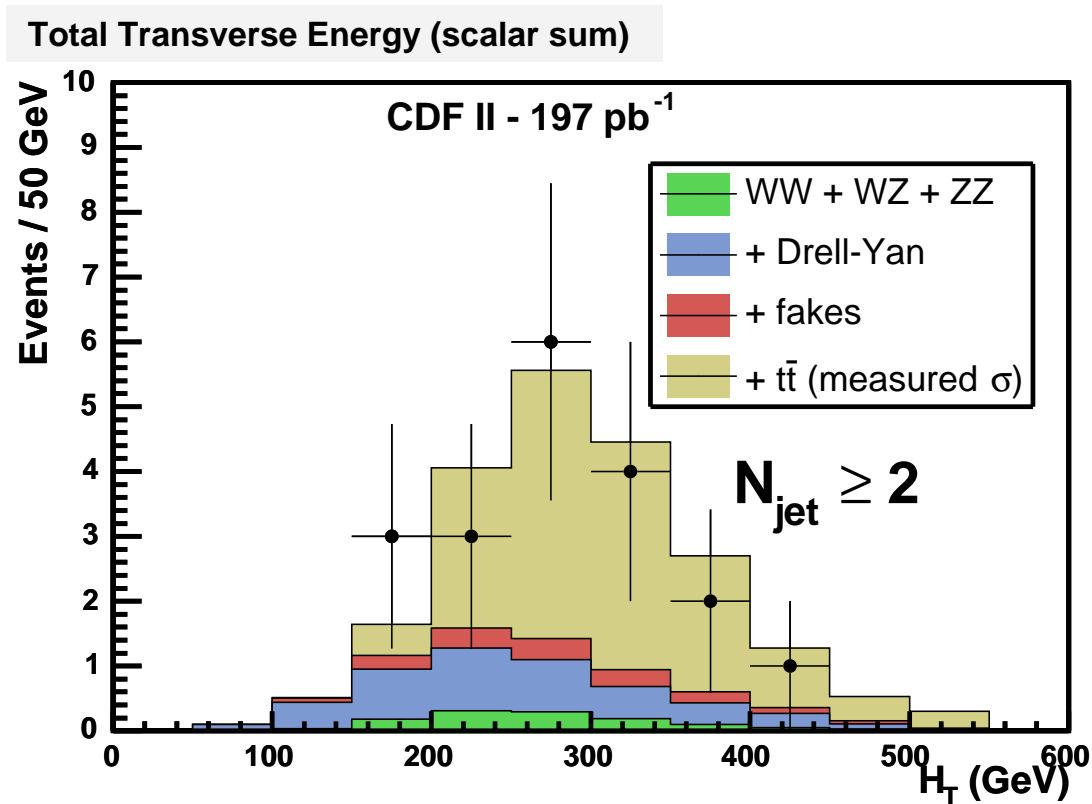
$H_T$  = scalar sum of  
transverse energies of  
all leptons, jets and  
missing  $E_T$

→ could be dangerous for  
some analyses

- This is a result of the  $b$ 's being produced entirely from gluon splitting and a  $q\bar{q}$  initial state, so probably not true when generalizing to higher jet multiplicities → good news

# Top dilepton cross-section

- $H_T$  is a useful quantity for picking out events containing top (or any other heavy particle)

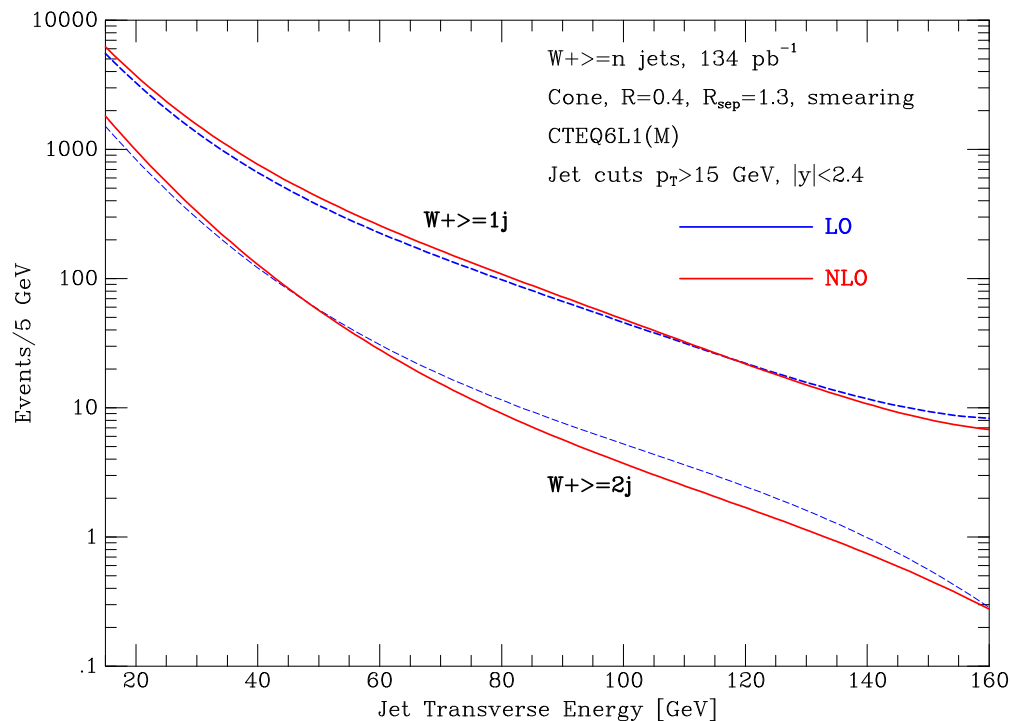


C. Hill et al., CDF collaboration, hep-ex/0404036

# Run II NLO comparisons with data

■ Nothing at present - no NLO comparisons yet in Run II. Issues:

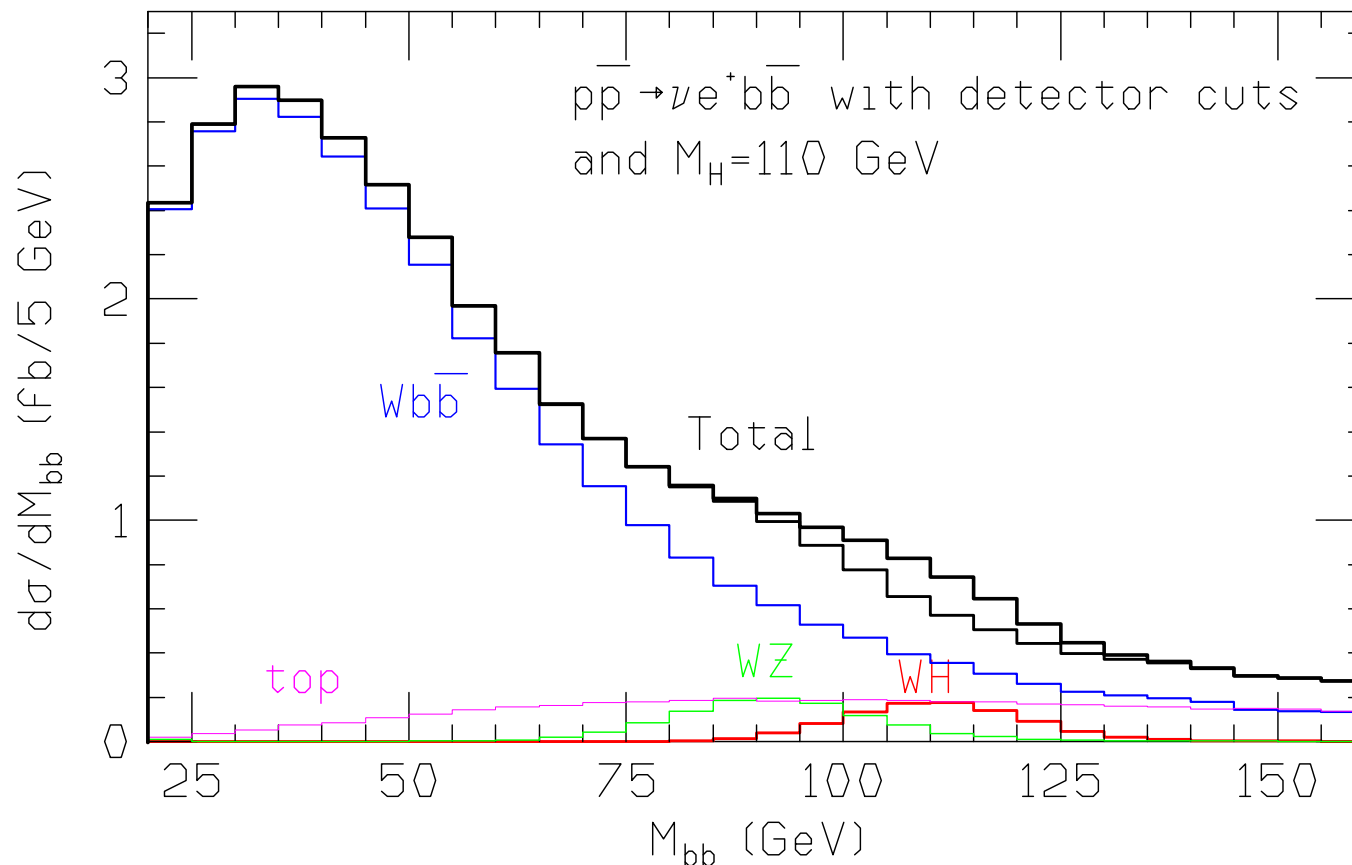
- ★ jet algorithm:  $k_T$  vs. JETCLU
- ★ smearing to simulate detector resolution
- ★ no hadronization in a parton level calculation



# Searching for $WH$

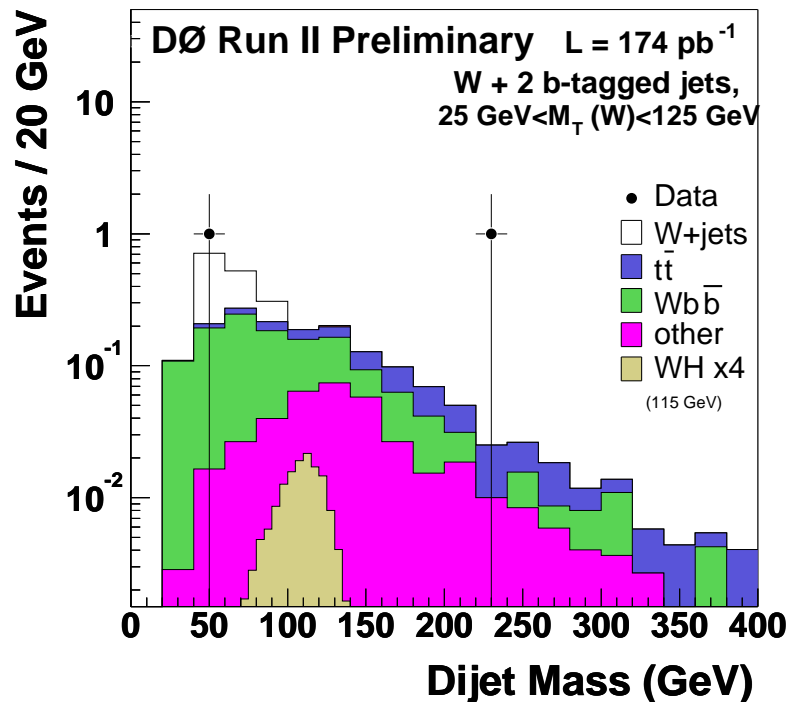
signal :  $p\bar{p} \longrightarrow W(\rightarrow e\nu) H(\rightarrow b\bar{b})$

largest background :  $p\bar{p} \longrightarrow W(\rightarrow e\nu) g^*(\rightarrow b\bar{b})$



# *WH cross section from D0*

- Improved limit based on  $174 \text{ pb}^{-1}$  of data
- Requires 2  $b$ -tags by all three algorithms.
- Background shape calculated using ALPGEN, but normalized to NLO. Good agreement found with the single  $b$ -tag sample.

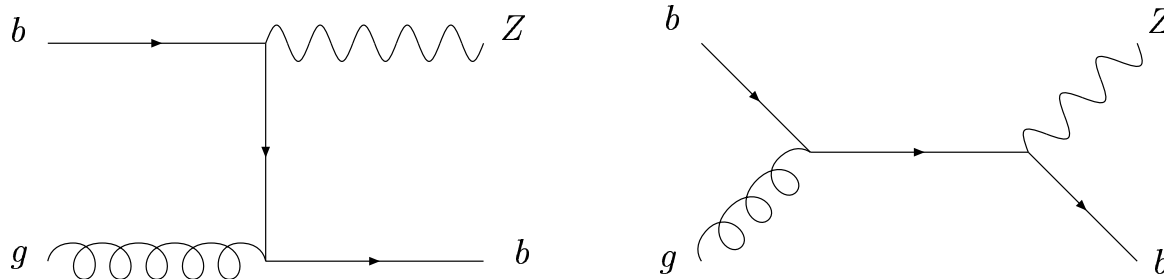


$$\sigma(WH) \times BR(H \rightarrow b\bar{b}) < 12.4 \text{ pb}$$

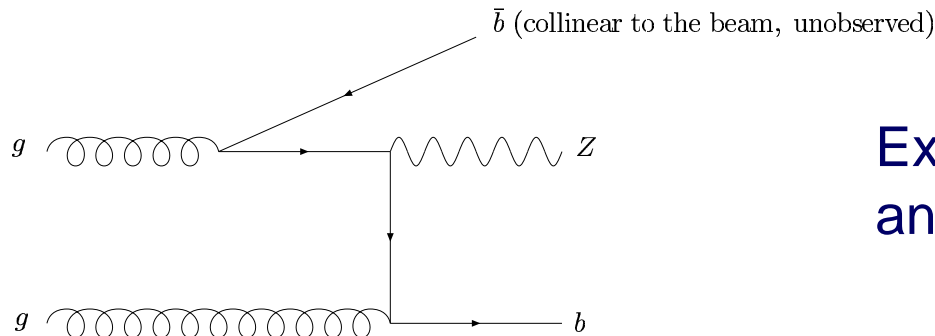
for  $m_H = 115 \text{ GeV}$

# Heavy flavour fraction revisited

- Often the presence of two  $b$ -quarks in the final state is actually only inferred from a single  $b$ -tag
- In this case, there is another way of computing the theoretical cross-section, for instance:



- Requires knowledge of  $b$ -quark pdf's, but compare to:



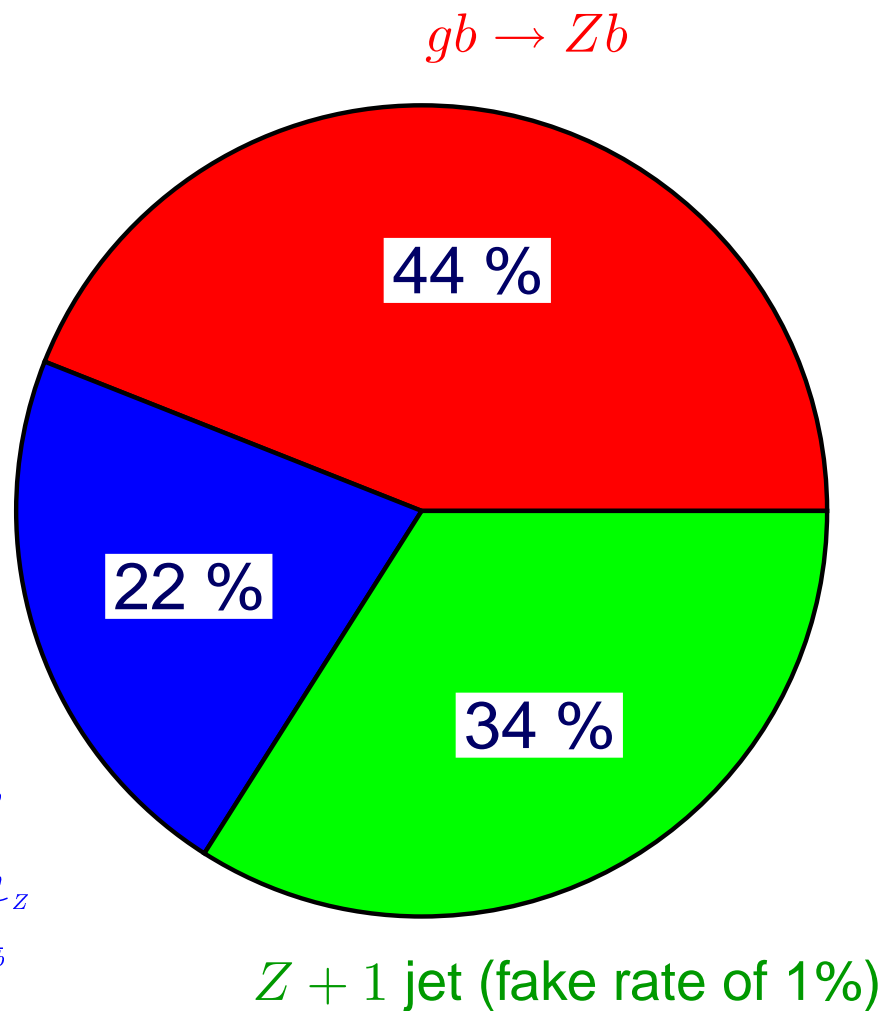
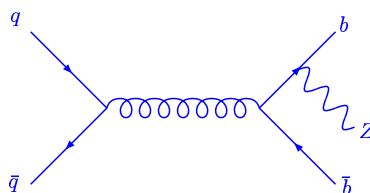
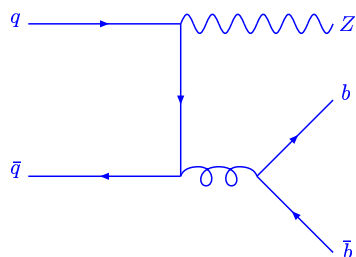
Expansion in  $\alpha_s \ln(M_Z/m_b)$   
and NLO calculation difficult

# $Z + b$ at NLO - Run II

JC, K. Ellis, F. Maltoni and S. Willenbrock, hep-ph/0312024

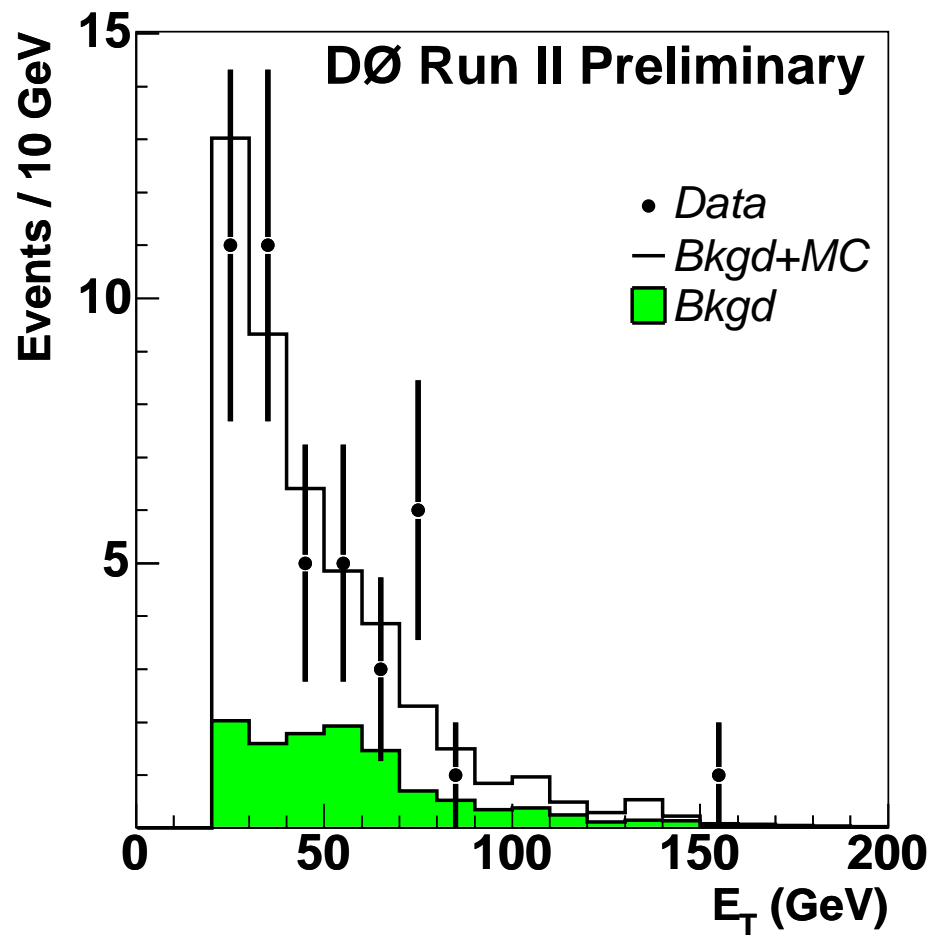
- $p_T^{\text{jet}} > 15 \text{ GeV}, |\eta^{\text{jet}}| < 2$
- $\sigma(Z + \text{one } b \text{ tag}) = 20 \text{ pb}$
- Fakes from  $Z + \text{jet}$  events are significant
- Prediction for ratio of  $Z + b$  to **untagged**  $Z + \text{jet}$  is  $0.02 \pm 0.004$

$$q\bar{q} \rightarrow Z(b\bar{b})$$



# Experimental result

■ Based on  $189 \text{ pb}^{-1}$  of data from Run II



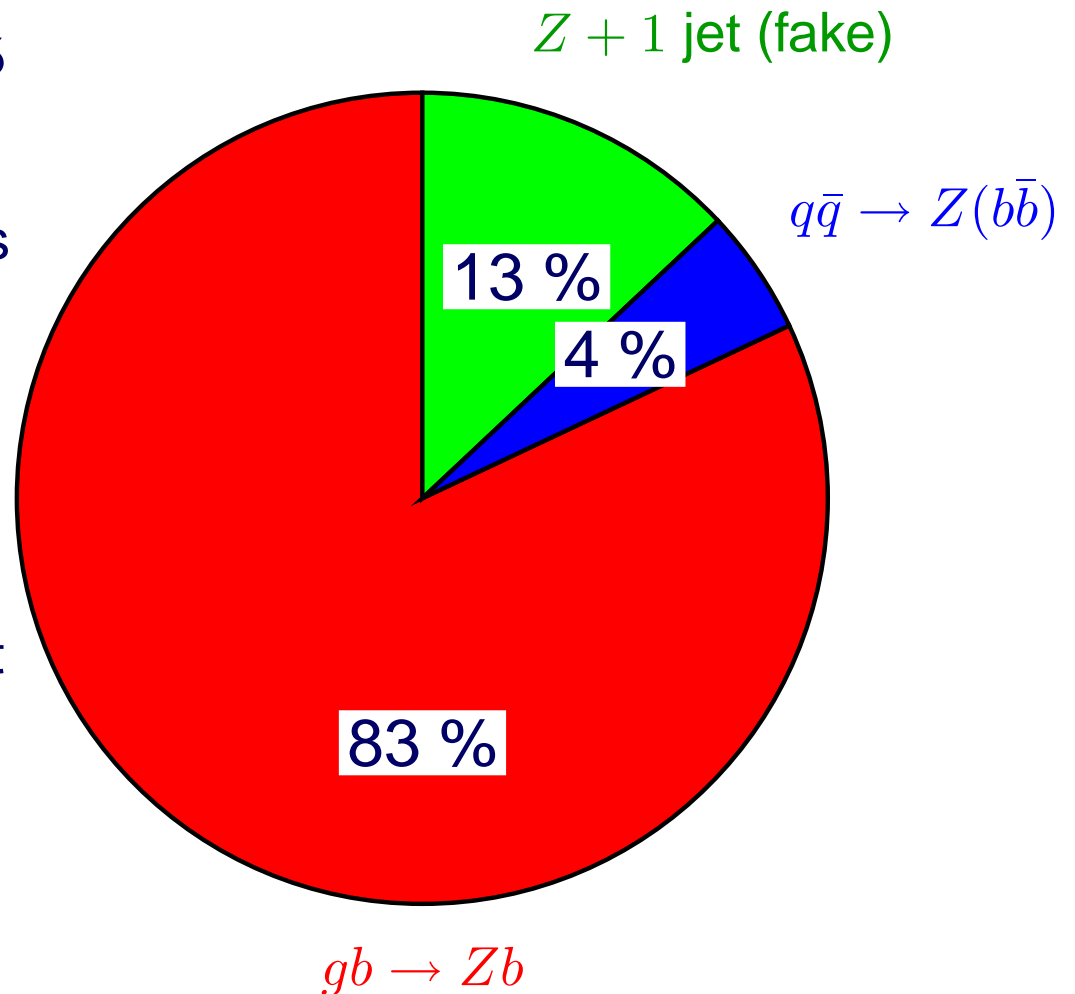
Preliminary ratio of cross-sections:

$$\frac{\sigma(Z+b)}{\sigma(Z+j)} = 0.024 \pm 0.07$$

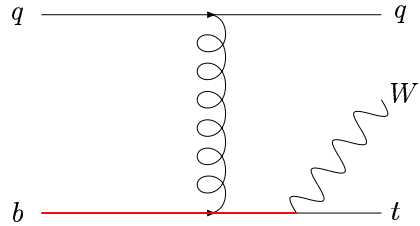
compatible with the NLO prediction.

# *LHC expectations*

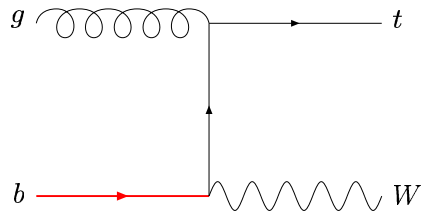
- $p_T^{\text{jet}} > 15 \text{ GeV}, |\eta^{\text{jet}}| < 2.5$
- $\sigma(Z + \text{one } b \text{ tag}) = 1 \text{ nb}$
- Fakes from  $Z + \text{jet}$  events are much less significant and  $q\bar{q}$  contribution is tiny
- This should allow a fairly clean measurement of heavy quark PDF's (currently, only derived perturbatively)



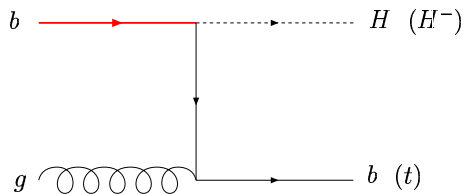
# *b*-PDF uses



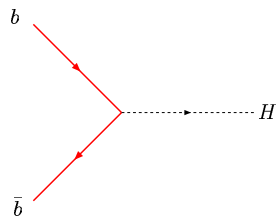
single-top  $qb \rightarrow qtW$



single-top  $gb \rightarrow tW$



(charged) Higgs+b



inclusive Higgs

# Calculations needed

- Improved NLO - for instance, the inclusion of  $b$  mass effects in  $Wb\bar{b}$  and  $Zb\bar{b}$ 
  - ★ Technology is available, efforts are underway . . . c.f.  $Hb\bar{b}$ 
    - W. Beenakker et al., hep-ph/0211352
    - S. Dawson et al., hep-ph/0311216
- Higher jet multiplicity calculations at NLO
  - ★ A distant goal, probably not in time for Run II
    - Nagy and Soper, hep-ph/0308127
    - Giele and Glover, hep-ph/0402152
- Merging of existing NLO calculations with a parton shower
  - ★ MC@NLO has yet to be applied to  $W/Z + \text{jets}$
- Further study of new ideas regarding parton showers
  - ★ How much of the effects of NLO are taken into account by combining matrix element calculations with parton showers?

# Summary

- The production of a  $W$  or a  $Z$  in association with jets is interesting both as a test of QCD and as an important background for many new physics signals
- There were many analyses in Run I, but many of the comparisons were limited by the theoretical predictions available
- New tools are available for Run II studies and in most cases they have yet to be fully utilized
- Some studies are new and should help pave the way for the next generation of analyses at the LHC